Honors Undergraduate Research Thesis

Optimizing the Movement Control System of a Hexapedal Robot using Modified Coordinate Descent

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Abstract:

Bio-inspired legged robots may potentially have capabilities that traditional wheeled robots may not be able to provide. As these robots become practical for everyday life, their body shape, control system, and movement pattern need to be optimized to fit the expected functional capabilities. The objective of this proposed research project was to test strategies to simultaneously optimize both the body shape and movement strategies for a hexapedal (six-legged) robot to walk most effectively. Specifically, we hoped to use classical iterative optimization strategies to obtain optimal shapes for 3D printed legs with different properties such as length, shape, and center of mass, and simultaneously optimize the leg movement patterns to be appropriate for the chosen leg shape. Such simultaneous hardware and control system optimization have many open problems and may inspire the design and optimization of assistive devices and other robots. Due to time constraints, we primarily considered the optimization of the movement control system (without co-optimizing the body) using a modified version of a classical optimization technique called coordinate descent. We considered optimization using three variables: leg sweep, leg down, and duty factor. We found that the robot walking speed can reach an optimal value of 0.151 m/s with the converged parameter values set. In addition to executing these coordinate descents twice, we also performed three univariate parameter sweeps, one for each of these three variables, which fixing the other two at their default values. Overall, this thesis provides evidence for the efficacy of these univariate sweeps and sequential coordinate descent in obtaining the optimal value of the parameters, but more work is needed to automate the process and also make the process itself optimized for rapid and reliable convergence.

Acknowledgments:

First, I would like to thank my research advisor Dr. Manoj Srinivasan for all the guidance in the last two years of my attachment in Ohio State University's Movement Lab as an undergraduate researcher. It's my pleasure to work with Dr. Srinivasan in multiple research projects, where I'm able to utilize my knowledge learned.

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Table of Contents:

List of Tables:

List of Figures:

Chapter 1: Introduction

1.1 Background

A hexapedal walking robot is a mechanical vehicle that moves on six legs with statically stable performance (figure 1). The design of some early hexapods is based on hexapedal insect locomotion, which provides a biological inspiration for the robot (Delcomyn and Nelson, 2000). Over the years, a number of research studies have been carried out on hexapod robots and have argued that these robots have great potential for practical applications (Saranli, 2001). Compared to other types of robots, hexapedal robots have higher stability and fault tolerance over diverse terrain (Tedeschi & Carbone, 2014). Due to its high performance and great mobility in different environments, hexapedal robots can be potentially used for remote area exploration, transportation of cargo, and rescue operations (Preumont, 1997).

However, the design and performance of most hexapedal robots cannot yet meet the requirements of practical applications. A lot of research projects have been done to improve the performance and efficiency of hexapeds (de Santos et al, 2009), but there have not been any that have been done on simultaneously optimizing the body or leg geometry and the movement control to improve performance. This research project aims to improve the movement of a hexapedal robot by replacing various actuators and legs on our version of an existing power autonomous legged vehicle, RHex (figure 2).

RHex is a powerful hexapedal robot that has six motors (actuators) and legs located at each hip for mechanical simplicity (Saranli, 2001). The robot to be used in our project is a smaller open-source version of the original design, called MiniRHex (figure 2). Similar to the original design, MiniRHex (Barragan et al, 2018) also has six curved legs connected to the motors at six hips. The robot is able to move in a robust and stable manner over different terrain by rotating six pedals in a certain algorithm (Altendorfer et al, 2001). In our project, we will improve the performance of the robot moving with different legs by systematically changing the leg geometry such as length, curvature, shape, and mass. The parameter sweep method and coordinate descent will be used in the analysis to optimize the movement and determine the optimal leg shape and properties.

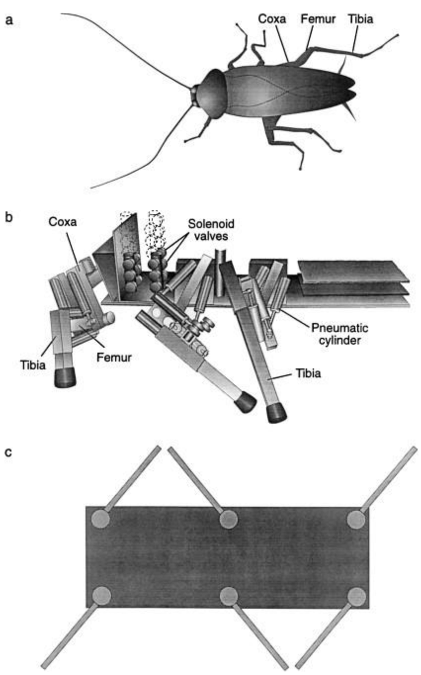

Figure 1: a) Cockroach is an inspiration for a hexapod robot. b-c) hexapod robot prototypes. (Image from Delcomyn, 2000)

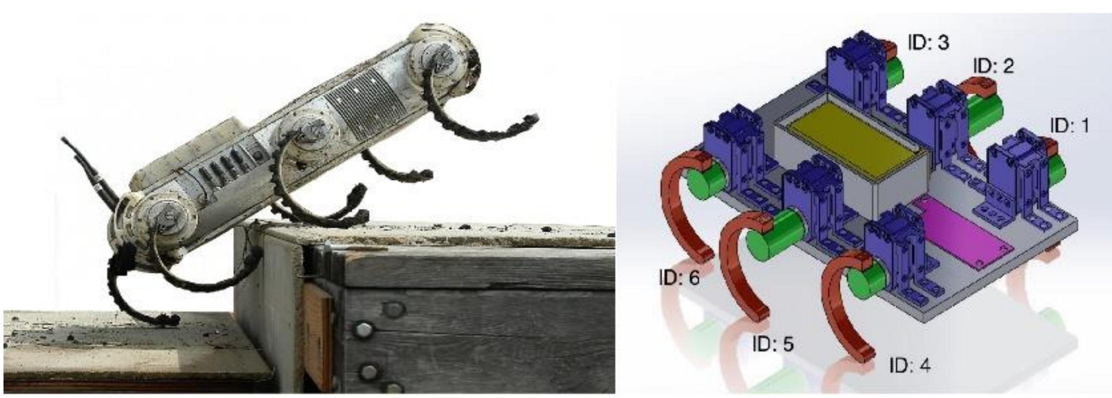

Figure 2: Left panel: RHex (Image from Boston Dynamics, n.d.). Right panel: MiniRHex Assembly (Image from Barragan et al, 2018)

1.2 Purpose of Research

The objectives of this project are to:

- Utilize 3D printer and laser cutting to construct robot parts. Assemble the basic version of the robot.
- Design various types of alternate leg components with CAD software such as Solidworks.
- Utilize motion capture to measure the movement of the robot. Perform parameter sweeps to understand the effect of various parameters. Analyze motion data with MATLAB.
- Apply coordinate descent to optimize robot.
- Determine the robot body and control that maximizes the robot performance. Due to time constraints, we revised our goals to examine only the optimization of movement control parameters.

1.3 Literature Review

1.3.1 Existing Hexapod Prototypes

The design of most hexapods is initially based on hexapedal insect locomotion such as a cockroach (figure 1). The robot shown in figure 3 is designed with insect-like keg structure and actuators that mimic the movement of the American cockroach (Delcomyn, 2000). The research team that develops this prototype model it after the cockroach because of its extraordinary speed and high agility. Also, compared to other legged insects that have a more complicated structure and movement algorithm, the structure and physiology of a cockroach are reasonably well known. The robot has six actuators with six legs attached and the six legs are employed with three segments each to mimic the insect. Each leg segment has a different length and structure.

The robot we are using in this project is called MiniRhex (Barragan et al, 2018) and it is a small scaled version based on the Rhex hexapod. Different from some early prototypes introduced above, Rhex has a unique and simple design. Rhex has only six actuators (motors) located at each hip (figure 4). The legs rotate in a full circle with three legs in a group to push the robot forward. The robot has strong mobility and maneuverability over diverse terrain (Saranli, 2001). The research team conducted multiple tests to justify the high performance of Rhex on different surfaces (Table 1). The results indicate RHex has great potential in terms of maneuverability in various settings.

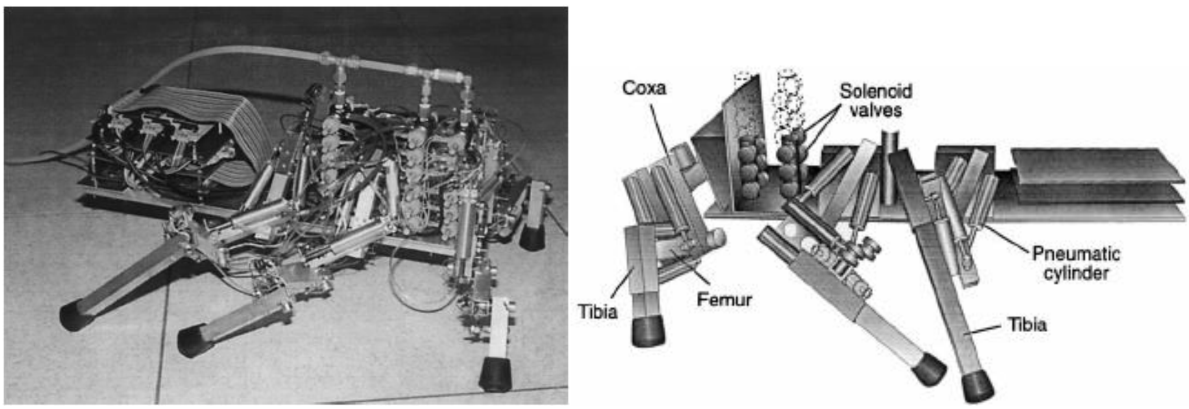

Figure 3: Picture of Biobot and leg segments of Biobot (Image from Delcomyn, 2000)

Figure 4: Picture of Rhex (Image from Saranli, 2001)

	Carpet	Linoleum	Grass	Gravel	Rough	Single Obstacle	Comp. Const.	Obstacle Course
Total number of runs	10	11	16	25	32	14	14	26
Successful runs	10	10	10	10	16	10	10	10
Electronics and hardware problems	—	—	1	5	6	—	—	2
Deviation from course	—	1	—	5	7	—	—	5
Operator mistake[a]	—	—	5	5	—	3	2	2
Stuck on obstacle	—	—	—	—	3	1	2	7

Table 1: Experimental Statistics of Rhex (Table from Saranli, 2001)

1.3.2 Optimization of Hexapods

The optimization of hexapods has been a popular topic of research and study over the years (e.g., Weingarten et al, 2004). A considerable number of parameters can be potentially optimized in the system. The system parameters can be divided into two types: hardware and software parameters. The hardware parameters can be further classified into structural parameters, actuator parameters, and electronics parameters. The software parameters include actuator control parameters and walking parameters (Kecskés, 2009). Depending on the situation, the goals of optimization usually include:

- Achieving maximum speed of walking while consuming as little electric energy as possible.
- Minimizing discursion and inconsistency of torques on the joints and gears, as well as the currents of actuators.
- Minimizing robot body acceleration in all 3 dimensions while walking.
- Maximizing the payload while remaining the same robot functions.

The change of both hardware and software parameters will usually influence the optimal values of other parameters (Silva, 2009). This means that these parameters are not independent parameters. Trying out all the combinations of these parameters in experiments will be very time-consuming, so the computer simulation is generally be used (Székács, 2013). In addition to hexapod-specific optimization (Weingarten et al, 2004), there is a large and rapidly growing literature on robot-in-the-loop optimization either using, for instance, reinforcement learning and direct optimization.

1.4 Significance of Research

Hexapod robots have great potential due to their high mobility and performance across diverse terrain. These robots can be used in many fields such as remote area exploration, cargo transportation, as well as surveillance and rescue missions. Various prototypes of hexapods have been developed and studied by many researchers over the years, but the performance of most hexapod prototypes have not met the requirement of practical use. One concern of the performance is the relatively low walking speed. In order to improve performance, many control parameters can potentially be optimized. The parameters are not independent, meaning that the change of one parameter will affect the optimal value of the other. The research aims to co-optimize both hardware and software parameters of a hexapod to improve the walking speed. The parameters involved will be further explained in the methodology chapter. Whereas Weingarten et al, 2004 used the Nelder-Mead simplex method for hexapod optimization, here, we use a modified coordinate descent, which appears to have not previously been used in this context.

Chapter 2: Methodology

2.1 Experiment Outline in Brief

The project's objective is an optimization of the walking speed of a hexapod named MiniRhex. Both control parameters and physical parameters are supposed to be considered in the optimization process. Multiple optimization methods are supposed to be used during the process such as parameter sweep and coordinate descent. The project consists of two parts, which are the fabrication of the robot and the optimization of the performance. During fabrication, 3D printing and laser cutting technologies are used to create leg and body components of the robot, all the electrical components are purchased, and the robot assembled. For the optimization process, motion capture will be used to measure the performance and analyze the data. For each trial, the robot will be let to walking for 1 meter and the total travel time will be measured with motion capture. Each trial will repeat at least 3 times and the average of the 3 numbers will be recorded to reduce error.

2.2 Research Platform

2.2.1 Robot Details

The robot used in the experiment is MiniRHex developed by the Robomechanics Lab of Carnegie Mellon University based on the hexapod RHex. The intention of designing this robot was to provide an education or research platform for robot mechanics study. The low cost and simple structure, as well as the high performance, are the main features of this robot (Barragan et al, 2018). The comparison of MiniRhex and its full-sized prototype X-RHex are given in Table 2.

MiniRHex (figure 5) measures about 19 cm in length, 10 cm in width, and 6 cm in height. The structure of the robot is very simple, which includes one laser-cut base and six 3D printed servo sleeves and legs. The six one-degree-of-freedom legs are designed to be a compliant "C" shape to better navigate through diverse terrain. The robot moves by continually rotating six legs in a certain algorithm to push the whole structure forward. The controller and six actuators allow programming six legs together and separately. The parameters involved for programming including duty factor, leg sweep, leg down, and phase coherence, which will all be explained in detail in the optimization section.

Specification Chart	MiniRHex	X-RHex (2010)
Mass	.425 kg	8.6 kg
Carrying Capacity	1.8-3 kg	5-10 kg
Length	0.186 m	0.53 m
Width	0.100 m	0.39 m
Leg Diameter	0.058 m	0.175 m
Experimental Leg Spring Constant	1.98 N/mm	1.4-1.7 N/mm
Leg actuation	Dynamixel XL320 Servo	Maxon Brushless Motor
On-Board Processing	OpenCM9.04	PC104, Intel Atom Processor
Single Unit Price	< $250	~$20,000

Table 2: Robot Specifications of MiniRHex and X-Rhex (Table from Barragan et al, 2018)

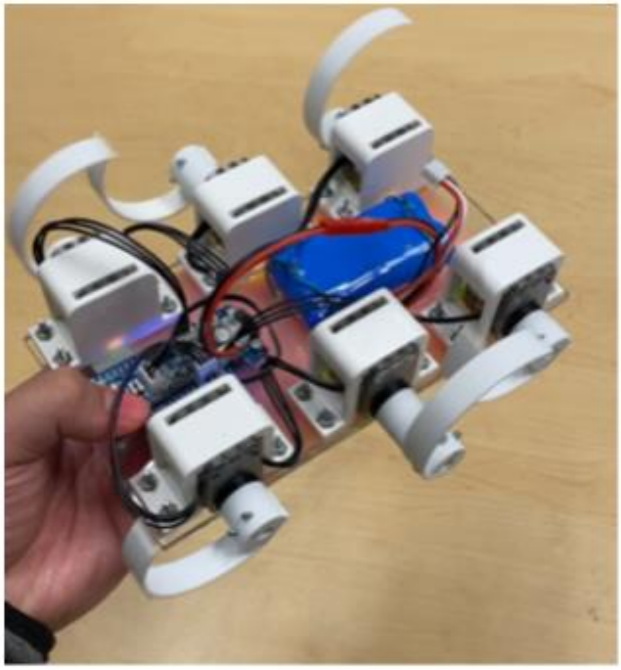

Figure 5: Our copy of MiniRHex that we fabricated at the Ohio State University

Part	Number	Weight (each)
Servo Sleeve	6	11g
Shaft-edge	4	3g
Shaft-mid	2	5g
Leg	6	2g
Battery Case	1	17g

Table 3: Robot Part List (Barragan et al, 2018).

2.2.2 Fabrication Details

The structure of MiniRHex mainly consists of one lacer cut base and six pairs of 3D printed servo sleeves and legs. The full list main components and their mass are listed in Table 3. After acquiring all the body components (figure 6), we made sure the size of holes fit the 3mm screws that is going to use later. We then attached the servo motors into the sleeve parts first before fixing them on the base. The next step is to install the six shafts on the servo motors and make sure shafts align the servo motor correctly. Then, we installed the middle two legs onto the two middle long shafts first before installing the other four legs. After installing all the structure components, we wired the servo motors and the controllers as Figure 7 shows.

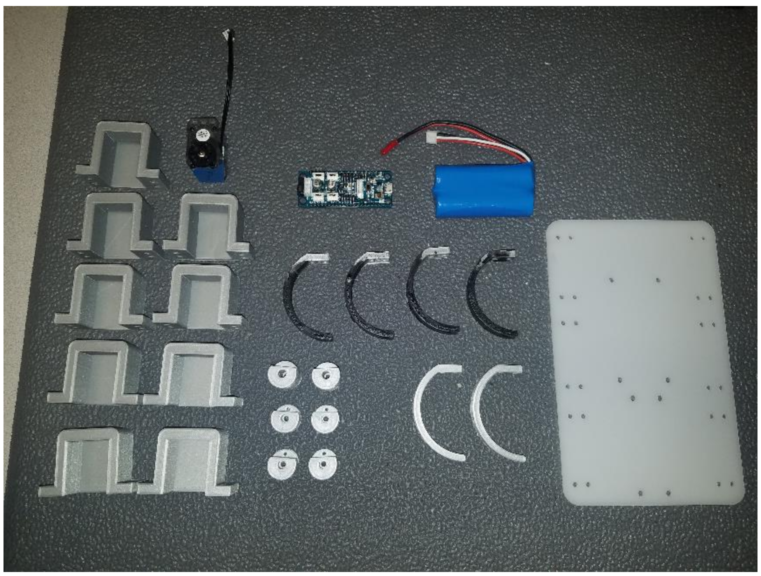

Figure 6: Picture of Main Parts of MiniRHex (Image from Barragan, 2018)

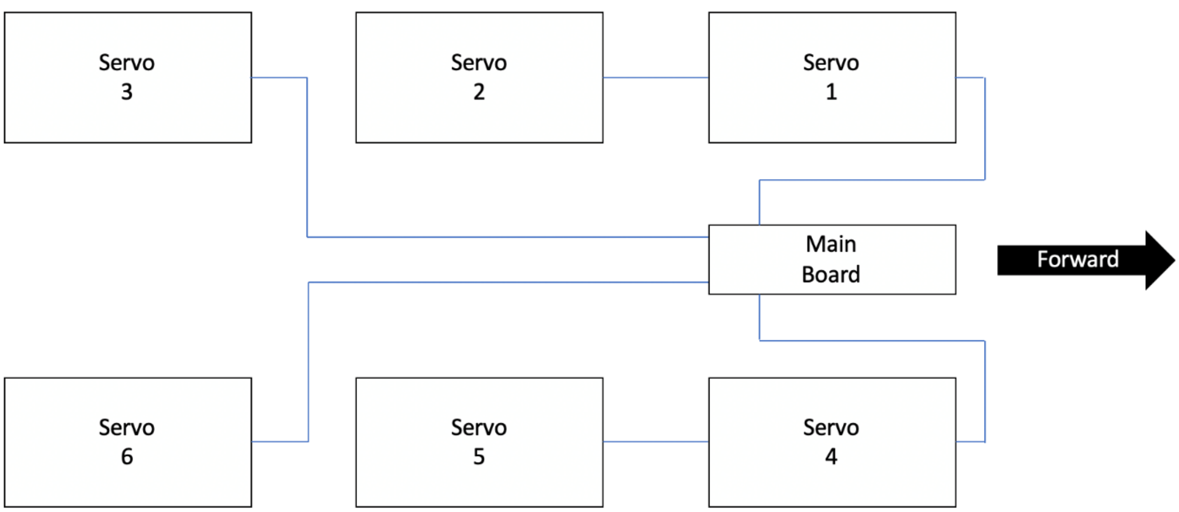

Figure 7: Wiring Layout of MiniRHex (Image from Barragan, 2018)

2.3 Optimization

2.3.1 Parameters

The optimization process of this project mainly focuses on improving the walking speed of the robot. The walking speed is an important factor to evaluate the performance of the hexapod walking robot. In order to optimize the walking speed, several parameters are considered in the experiment. The robot control parameters include duty factor, leg sweep, leg down, and phase coherence.

The duty factor is a common parameter to be evaluated during optimization for most walking robots. For MiniRHex, the duty factor means the percentage of time the leg is in a stance position. Stance position is the state that the leg physically touches the ground (figure 8). The duty factor ranges from 0 to 1. In this case, “0” means the legs are never in contact with the ground (rotates fast) and “1” means that the leg is always in contact with the ground (always in slow phase).

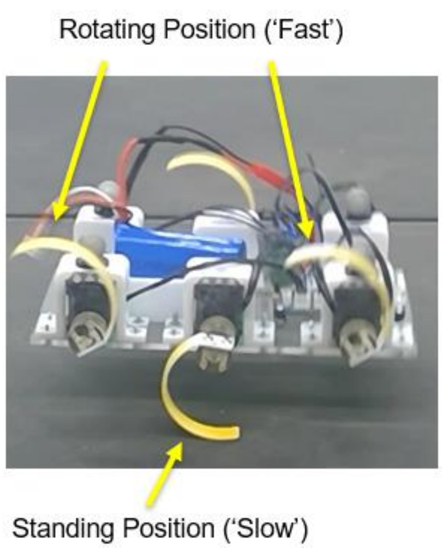

Figure 8: Duty Factor

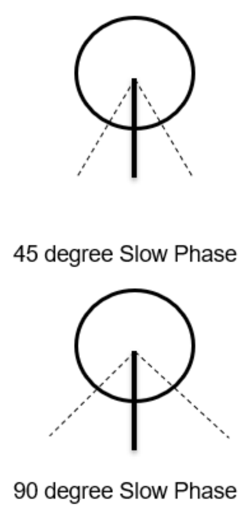

Figure 9: Leg Sweep illustration

Leg sweep angle is an important parameter to be considered for MiniRhex particularly. Leg sweep is defined as the angle width of stance position ("slow phase") while walking (figure 9). Leg sweep could range from 0 to 360 degrees, where 0 degree means there is no slow phase and 360 degrees means entire rotation is in a slow phase. In the experiment, a reasonable range of 20 to 180 degrees are chosen.

Leg down angle is another unique control parameter for MiniRHex. Leg down is defined as the center angle of the slow phase. The range of leg down angle is from 0 to 360 degrees. The angle is measured from the position where the centerline of the leg is perpendicular to the ground as shown in Figure 10. In the experiment, an effective range of 10 to 100 degrees is chosen to avoid extreme values.

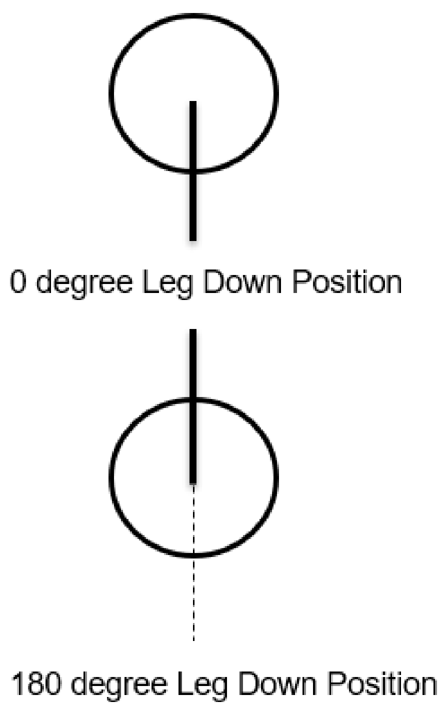

Figure 10: Leg Down Angle illustration

2.3.2 Optimization Methods

The optimization methods used in the experiment are mainly parameter sweep and coordinate descent. In parameter sweep, a list of values of the certain control parameter is chosen and the performance of the robot is measured under each selected value. The coordinate descent method is the optimization of more than two parameters simultaneously. In coordinate descent, a line search is performed for one selected control parameter for each iteration to find the optimal value (line search simply means 'search along a line' or a one-variable optimization). The second line search is performed for another control parameter while keeping the first optimal value unchanged. The same process is repeated for the rest of the parameters and the first iteration is completed. Multiple iterations should be performed to find the optimal parameter values for best performance (figure 11). In this thesis, a modified coordinate descent method is used. For each iteration, a coarse parameter sweep is performed for each control parameter.

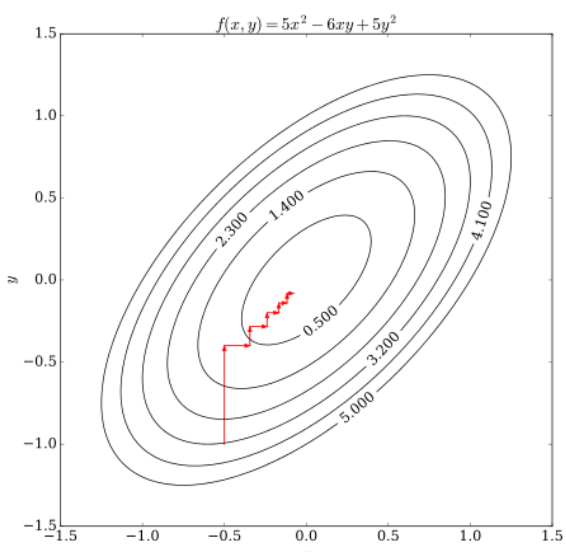

Figure 11: Coordinate Descent Example (Wright, 2015). We see that sequence of iterations move along a perpendicular direction, performing line searches along each direction, eventually converging to a minimum. Image from Nicoguaro / CC BY (https://creativecommons.org/licenses/by/4.0/)

2.4 Experiment

2.4.1 Setup and Instrument

The reflective-marker-based motion capture and video-based analysis are two major methods for motion data collection. Video analysis is mainly used in data collection for our parameter sweeps. The speed of the robot is measured by looking at each frame of the video. During data collection, the camera is fixed to include the robot as well as two lines that mark the length of one meter on the ground (figure 12). The frame number is recorded as the front of the robot passes the “starting line” mark and the “finish line” mark so that the total walking time can be calculated.

We intended to use 3D marker-based motion capture (Vicon Inc.) for coordinate descent data collection. The coordinate descent requires the real-time robot performance data after each run, so the video analysis is no longer viable. The motion capture collects the coordinate position of the robot in real-time and streaming to PC, which allows real-time analysis of motion data (figure 13). Four reflective markers are fixed to the MiniRHex and the two reflective dots are placed at the starting point and endpoint respectfully (figure 14). The surrounding cameras capture the real-time position of all the reflective markers. The motion data will be analyzed after each run to get the performance.

Due to early lab closure on account of COVID-19, we were unable to have access to the motion capture system. Therefore, we reverted to using stop-watch-based timing to estimate the speed of the robot during the coordinate descent optimization. In the presence of mocap, we would have used real-time capture of markers and adaptation of robot parameter values, all from a single MATLAB program that also performed coordinate descent – so that the optimization process is entirely automated except for returning the robot to the initial position on the treadmill.

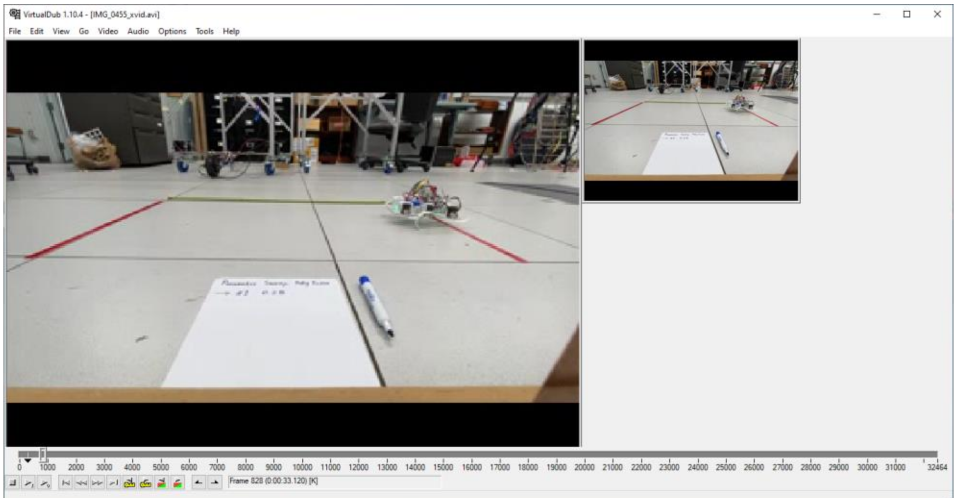

Figure 12: Video Analysis Setup, showing start and finish lines in red.

Figure 13: Motion Capture Setup in The Ohio State University: Movement Lab

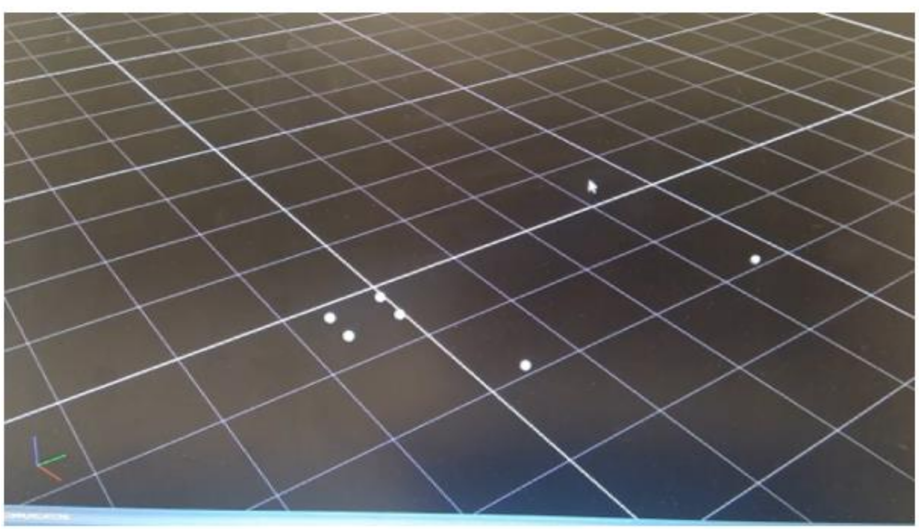

Figure 14: Motion Capture: Realtime Marker Positions

Chapter 3: Results and Discussion

3.1 Parameter Sweeps

In this section, we discuss the results of parameter sweep for univariate optimization. Parameter sweeps are performed on all three control parameters, which include duty factor, leg sweep, and leg down. Another important leg control parameter is the phase coherence and the experiment on this parameter was performed by another undergraduate researcher at OSU's Movement Lab (Khan, 2019). Coordinate descent on selected control parameters is performed after the three-parameter sweeps. The coordinate descent optimizes the three control parameters at the same to find the optimal value for robot walking speed.

3.1.1 Optimization Results with Parameter Sweeps

The total walking time of the robot to walk for one meter is the key metric to determine the performance in this optimization process. For each control parameter, a list of equally spaced values with random order is generated within the range limit. The robot is set to run at least three times with each value and the run times are recorded for calculation of walking speed. The default values of the three parameters are: -- for blah, -- for blah, and – for blah. We keep two of the parameters at their default values when we change the third.

For the duty factor parameter sweep, a list of values 8 values ranging from 0.10 to 0.65 are put in random order and the robot is set to run under these values accordingly. The summarized results are plotted with walking speed versus duty factor values (figure 15). For each duty factor, the mean walking speed is labeled with a blue cross. The maximum speed and minimum speed (from the three trials per parameter value) are labeled with dots with different colors. According to the diagram, the top walking speed is 0.146 m/s at the minimum duty factor value of 0.10. As the value of duty factor increases, the walking speed gradually decreases till the local minimum value of 0.037 m/s at a duty factor value of 0.56. The walking speed remains approximately the same after that point. The duty factor is the percentage of time the leg is in standing position. By definition, the leg rotation speed will increase as the duty factor value decrease. The walking speed is directly associated with leg rotation speed. So, the walking speed will reach peak value with minimum duty factor value.

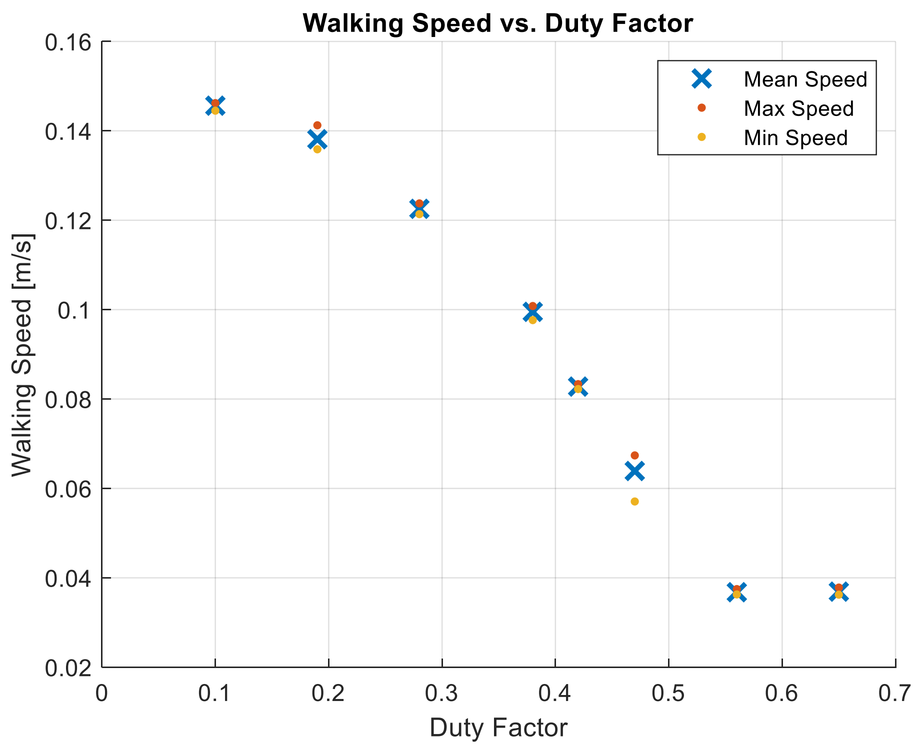

Figure 15: Diagram of Walking Speed over Duty Factor

For leg sweep parameter sweep, a list of values 8 values ranging from 20 to 180 degrees are put in random order and the robot is set to run under these values accordingly. The results are summarized by plotting walking speed versus the leg sweep values (figure 16). The labeling for the diagram is similar to figure 15. According to the diagram, the top walking speed is 0.125 m/s at a maximum leg sweep value of 180 degrees. As the value of the leg sweep angle increases, the walking speed gradually increases from a local minimum value of 0.041 m/s at a leg sweep angle of 20 degrees. Recall that the leg sweep angle is the angular width of the slow phase during rotation. Given other parameters remain unchanged, the time for one complete rotation should remain the same. Since the angular width of the slow phase is increased, the leg rotation speed for the fast phase will increase in order to control the time of each rotation.

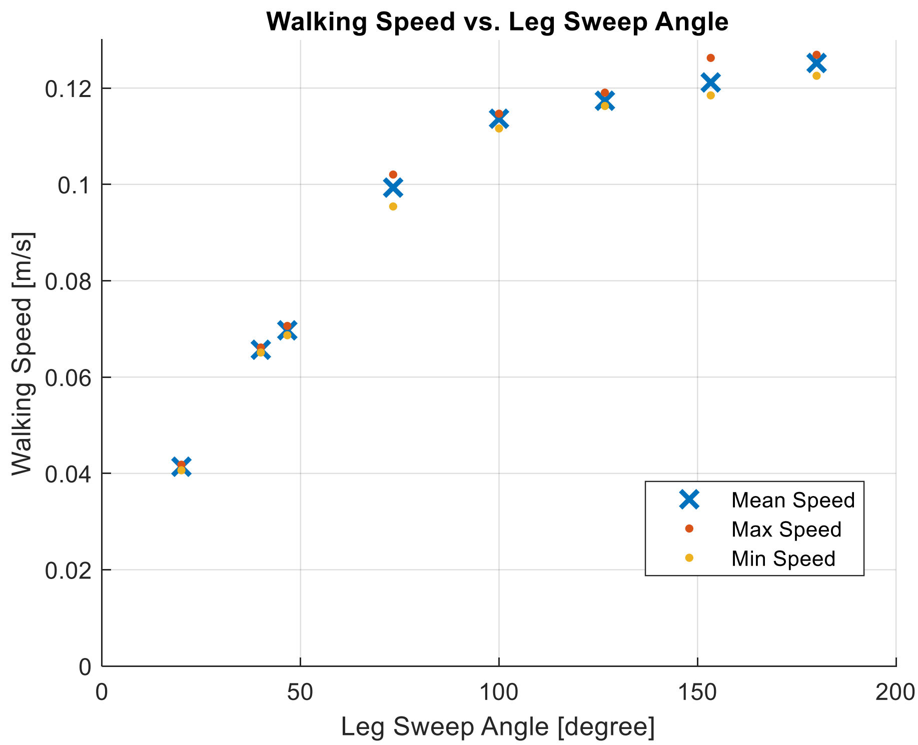

Figure 16: Diagram of Walking Speed over Leg Sweep Angle

The optimization for the leg down angle is similar to the previous two optimizations as well as the notation of the diagrams. The list of random values of leg down ranged from 10 to 100 degrees are chosen. According to figure 17, the walking speed reaches a maximum value of 0.129 m/s at the leg down angle of 55 degrees. As the leg down angle increases, the average walking speed increases almost linearly from a minimum value of 0.054 m/s to the peak value. Then the walking speed slowly decreases to a steady value of approximately 0.120 m/s.

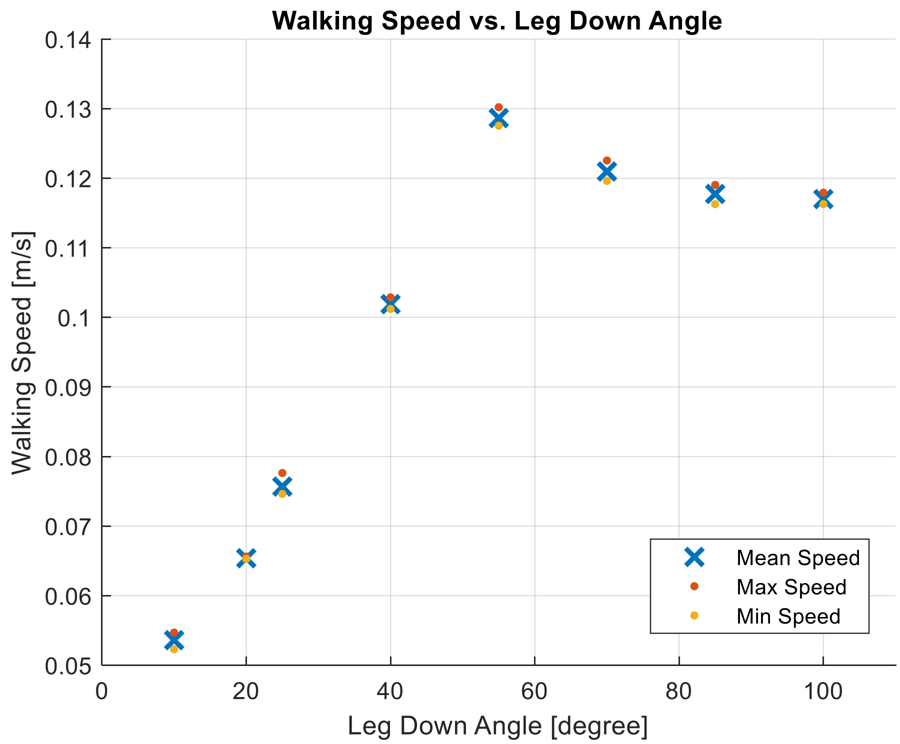

Figure 17: Diagram of Walking Speed over Leg Down Angle

3.1.2 Trial to Trial Consistency

Trial to trial consistency is an important factor to determine if the data collection method and performance of the robot are capable of repeated tests. In this experiment, the consistency is evaluated based on the effect of walking speed and magnitude of control parameter values on the standard deviation of measured data. For each trial, the data for a total number of three runs are recorded. The standard deviations of the three walking speed values are calculated and plotted against the corresponding parameter values (figure 18). The standard deviation for walking speed in each trial is small compared to the speed values and its magnitude varies for different parameter values. According to the diagram, no direct relationship between the standard deviation of walking speed values and parameter values is overserved. The values of standard deviation are randomly distributed across the range of all three control parameters. The standard deviation versus walking speed diagram has a similar situation (figure 19). No direct or clear relationship is observed between the standard deviation of walking speed values and walking speeds.

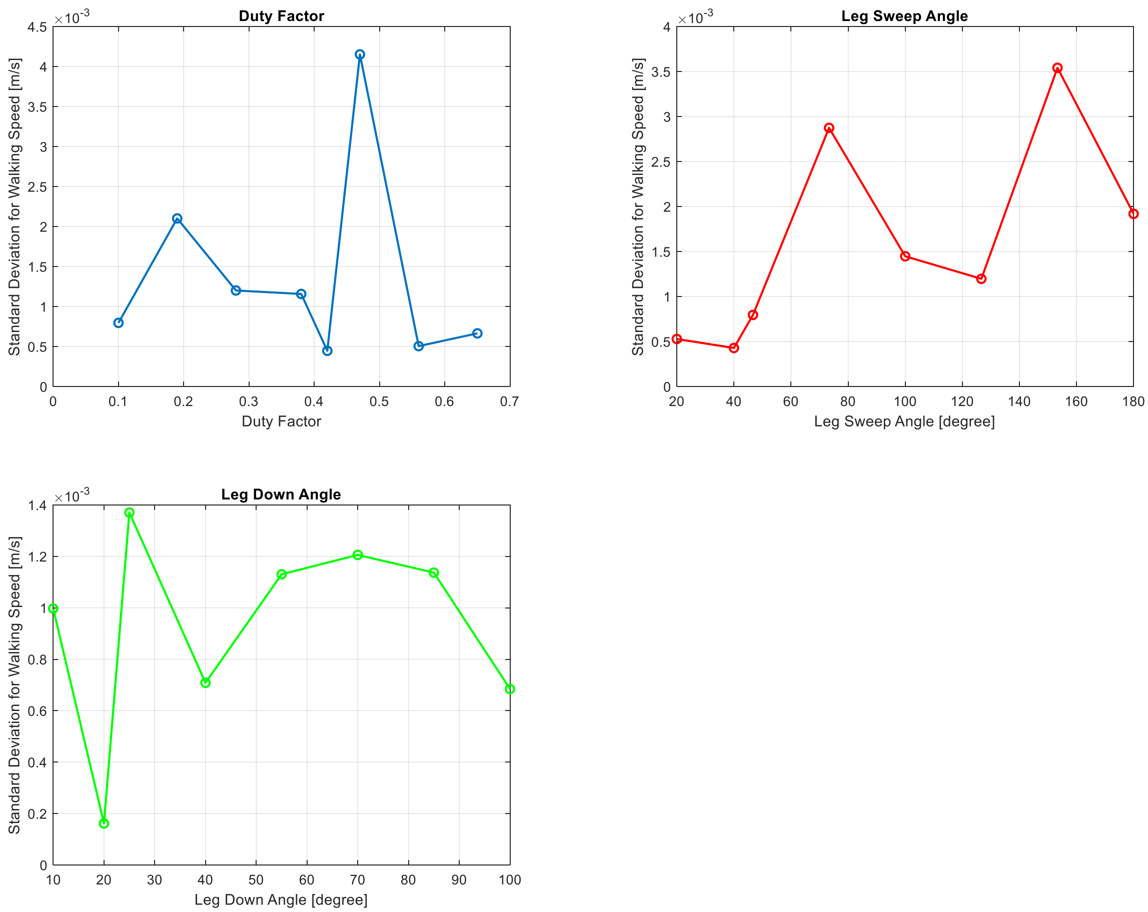

Figure 18: Trial to trial standard deviation over trials, for each of the three control variables.

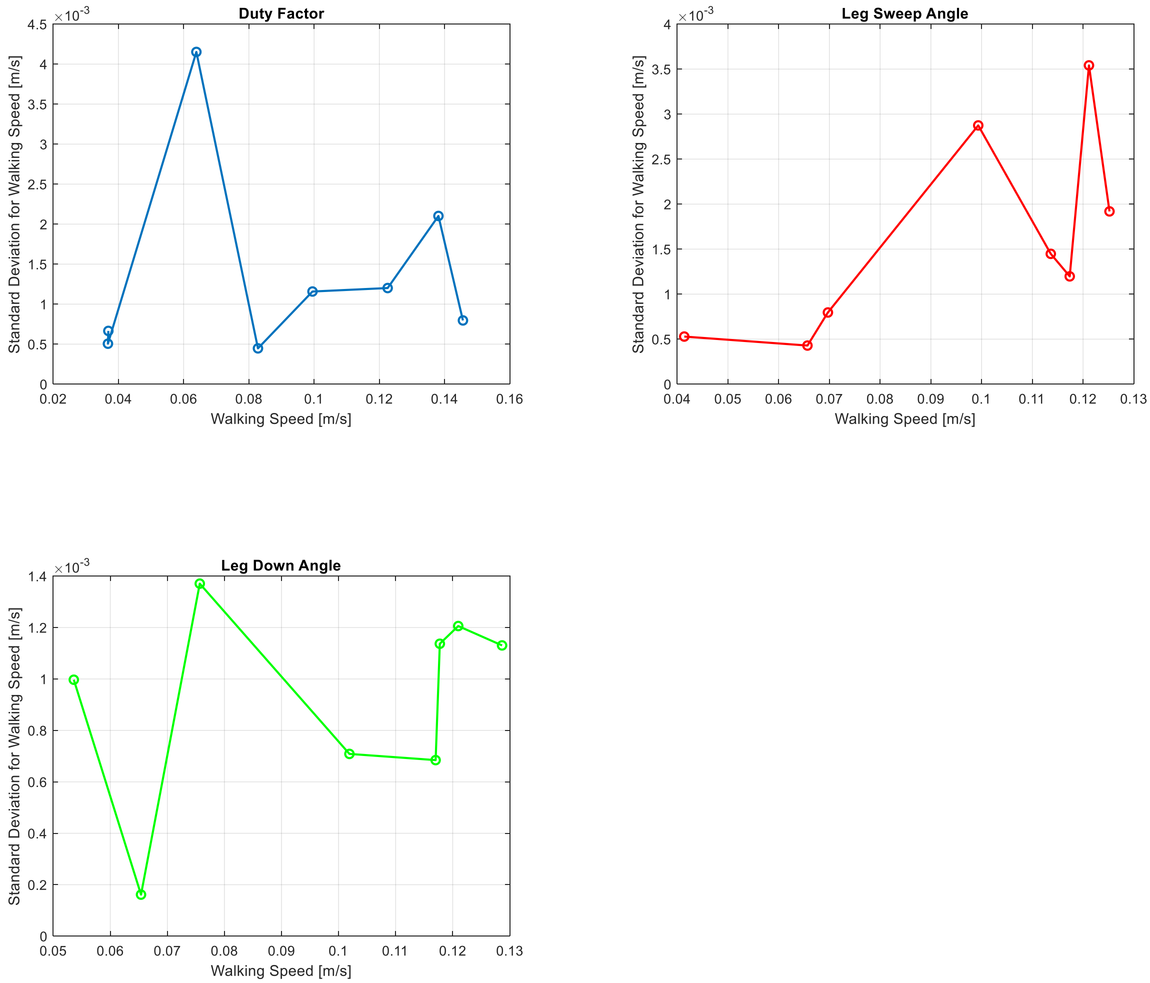

Figure 19: Trial-to-trial standard deviation over three trials per control parameter value, plotted versus corresponding walking speed values. No trend is observed with respect to the walking speed.

3.2 Coordinate Descent

The coordinate descent method focuses on improving the walking speed by optimizing all three control parameters mentioned above, which include duty factor, leg sweep angle, and leg down angle. We used a 'modified coordinate descent' where instead of a local line search, we use a global parameter search along with each control parameter. For each iteration, a list of N = 7 equally-spaced values is determined, spanning the range of all three parameters (table 4). One of these values is chosen for each control variable: the robot is then set to run with these parameter values and the walking time is recorded to calculate the walking speed of the robot. Then, we keep two of the three control variables fixed, and change one variable through the N = 7 possibilities. After running the robot with all the N values in the list, the value that gives the highest speed is kept. The same process is repeated for each of the other two control variables while keeping the other variables fixed. Each iteration will provide a list of optimal control parameter values. The optimization process is complete when the robot walking speed can no longer be improved.

Trial	Leg Down Angle	Duty Factor	Leg Sweep Angle
1	10.00	0.10	20.00
2	28.33	0.20	46.67
3	46.67	0.30	73.33
4	65.00	0.40	100.00
5	83.33	0.50	126.67
6	101.67	0.60	153.33
7	120.00	0.70	180.00

Table 4: List of Control Parameter Used

In the first coordinate descent we performed, starting from default values of the three parameters, the optimization process takes only two iterations to converge, where convergence is defined as two cycles yielding the same value. The first iteration results in a maximum speed of 0.1459 m/s and the second iteration results in a maximum speed of 0.1468 m/s with the same parameter values as in the first iteration (table 5). According to the data collected, the local optimal values for each parameter are also the global optimal values. The values of the three control parameters that gives the best performance are duty factor of 0.50, leg sweep angle of 46.67 degrees, and leg down angle of 65.00 degrees The results of the optimization are close to the default settings (duty factor: 0.42, leg sweep: 40, leg down: 20), suggesting that the default values were close to optimal.

Iteration 1						
Initial parameter values		Leg down	Duty factor	Leg sweep	Speed (m/s)	
		65.00	0.42	40.00	0.14098	
What is changed		Leg down	Duty factor	Leg sweep	Speed (m/s)	Standard deviation
Leg down	1	65.00	0.42	40.00	0.14098	0.001358
Leg down	2	101.67	0.42	40.00	0.13021	0.003683
Leg down	3	120.00	0.42	40.00	0.12793	0.001779
Leg down	4	28.33	0.42	40.00	0.10858	0.003427
Leg down	5	83.33	0.42	40.00	0.13010	0.003425
Leg down	6	10.00	0.42	40.00	0.06640	0.000108
Leg down	7	46.67	0.42	40.00	0.13333	0.004943
Duty factor	1	65.00	0.50	40.00	0.14225	0.000496
Duty factor	2	65.00	0.30	40.00	0.13630	0.004538
Duty factor	3	65.00	0.70	40.00	0.13889	0.000720
Duty factor	4	65.00	0.60	40.00	0.12341	0.004720
Duty factor	5	65.00	0.20	40.00	0.13316	0.003027
Duty factor	6	65.00	0.10	40.00	0.13544	0.001208
Duty factor	7	65.00	0.40	40.00	0.12386	0.003798
Leg sweep	1	65.00	0.50	73.33	0.01364	0.002946
Leg sweep	2	65.00	0.50	126.67	0.00789	0.002683
Leg sweep	3	65.00	0.50	100.00	0.01000	0.000285
Leg sweep	4	65.00	0.50	153.33	0.00652	0.002553
Leg sweep	5	65.00	0.50	180.00	0.00556	0.001500
Leg sweep	6	65.00	0.50	20.00	0.05000	0.002268
Leg sweep	7	65.00	0.50	46.67	0.14591	0.000503
Iteration 2						
Initial parameter values		Leg down	Duty factor	Leg sweep	Speed (m/s)	
		65.00	0.50	46.67	0.14684	
What is changed		Leg down	Duty factor	Leg sweep	Speed (m/s)	Standard deviation
Leg down	1	65.00	0.50	46.67	0.14684	0.001390
Leg down	2	101.67	0.50	46.67	0.12215	0.005420
Leg down	3	28.33	0.50	46.67	0.10733	0.001832
Leg down	4	120.00	0.50	46.67	0.12537	0.000924

Leg down	5	46.67	0.50	46.67	0.13717	0.004534
Leg down	6	83.33	0.50	46.67	0.13501	0.002053
Leg down	7	10.00	0.50	46.67	0.04437	0.001159
Duty factor	1	65.00	0.50	46.67	0.14684	0.004366
Duty factor	2	65.00	0.60	46.67	0.15940	0.005388
Duty factor	3	65.00	0.70	46.67	0.15213	0.005850
Duty factor	4	65.00	0.40	46.67	0.14265	0.001529
Duty factor	5	65.00	0.10	46.67	0.13953	0.001551
Duty factor	6	65.00	0.20	46.67	0.14634	0.004709
Duty factor	7	65.00	0.30	46.67	0.14677	0.001987
Leg sweep	1	65.00	0.50	153.33	0.13717	0.001414
Leg sweep	2	65.00	0.50	126.67	0.13514	0.000928
Leg sweep	3	65.00	0.50	46.67	0.14521	0.000865
Leg sweep	4	65.00	0.50	180.00	0.13280	0.004297
Leg sweep	5	65.00	0.50	100.00	0.14118	0.000656
Leg sweep	6	65.00	0.50	73.33	0.13993	0.001023
Leg sweep	7	65.00	0.50	20.00	0.13514	0.004919
Final result		**Leg down**	**Duty factor**	**Leg sweep**	**Speed (m/s)**	
		65.00	0.50	46.67	0.14521	

Table 5: Coordinate Descent on Walking Speed Results. Version 1.

Perhaps because the initial guess of the previous coordinate descent is already close to the optimal results, it only takes two iterations to converge. Seven values for each of the variables imply 7^3 = 147 combinations of parameters, whereas the two iterations only took about 44 parameter combinations, making the algorithm more efficient than evaluating all parameter combinations.

In order to investigate the system more, another simplified version of previous coordinate descent is performed starting with the worst parameter values from parameter sweeps. The new optimization takes four iterations to converge and the results are summarized in Table 6. (Note that this table records walking duration instead of walking speed.) In order to improve efficiency, a total of four values instead of seven values are chosen for each parameter and the robot is set run only one time per parameter set instead of using three trials per parameter set. Because we used one trial instead of three to evaluate the speed for each parameter set, the random error per evaluation may much higher. Due to this great uncertainty, the optimization method may not converge as expected. One example is in iteration 2 trial 4, the parameter used in this trial is exactly the same as the results from iteration 1, but the walking time value differs a lot, which may corrupt the optimization process. A plot of all the walking time data over the iteration numbers is created to show the trend of the optimization process (figure 20). The walking time duration (low speed) starts a high value due to the bad parameter settings and the walking time ends at close to the optimal values (as judged by our algorithm). Note that the two versions of the coordinate descent arrived at close to the same forward speed, within 0.006 m/s of each other, compared to a speed range 0.07 m/s during the optimization trials.

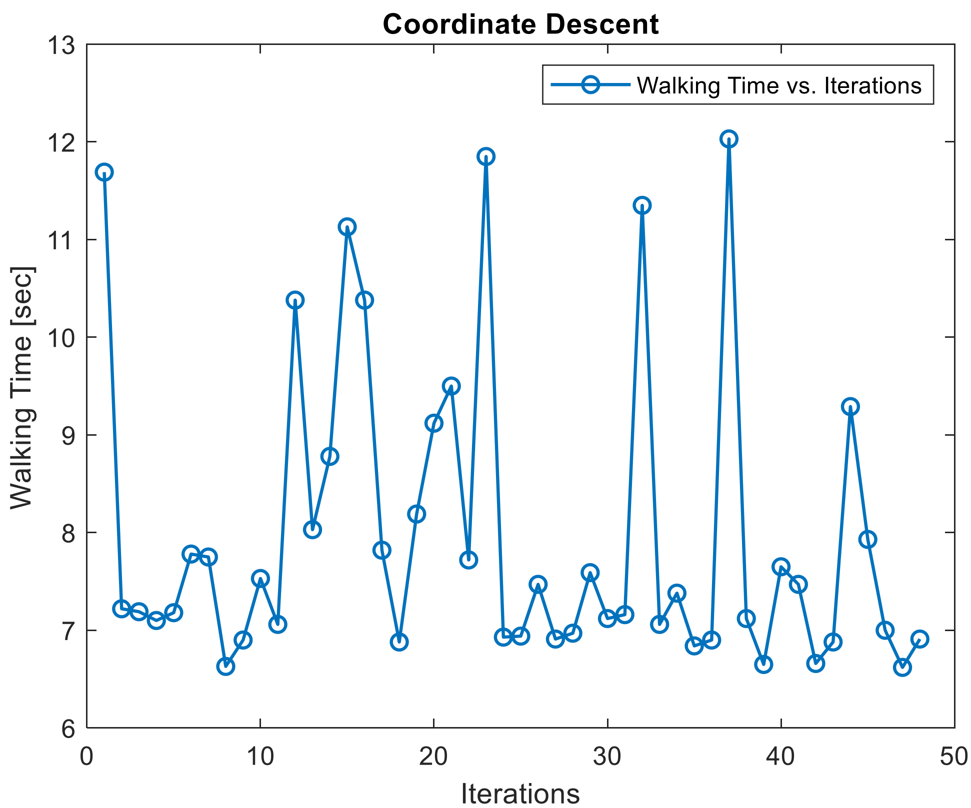

Figure 20: Coordinate descent, version 2. Optimization Results Over Iterations

Iteration 1						
Initial parameter values		**Leg down**	**Duty factor**	**Leg sweep**	**Time (sec)**	**Speed (m/s)**
		10.00	0.30	20.00	11.69	0.08554
What is changed		**Leg down**	**Duty factor**	**Leg sweep**	**Time (sec)**	**Speed (m/s)**
Leg down	1	10.00	0.30	20.00	11.69	0.08554
Leg down	2	83.33	0.30	20.00	7.22	0.13850
Leg down	3	46.67	0.30	20.00	7.19	0.13908
Leg down	4	120.00	0.30	20.00	7.10	0.14085
Duty factor	1	120.00	0.30	20.00	7.18	0.13928
Duty factor	2	120.00	0.50	20.00	7.78	0.12853
Duty factor	3	120.00	0.70	20.00	7.75	0.12903
Duty factor	4	120.00	0.10	20.00	6.63	0.15083
Leg sweep	1	120.00	0.10	20.00	6.90	0.14493
Leg sweep	2	120.00	0.10	126.67	7.53	0.13280
Leg sweep	3	120.00	0.10	73.33	7.06	0.14164
Leg sweep	4	120.00	0.10	180.00	10.38	0.09634
Iteration 2						
Initial parameter values		**Leg down**	**Duty factor**	**Leg sweep**	**Time (sec)**	**Speed (m/s)**
		120.00	0.10	20.00	6.90	0.14493
What is changed		**Leg down**	**Duty factor**	**Leg sweep**	**Time (sec)**	**Speed (m/s)**
Leg down	1	10.00	0.30	20.00	8.03	0.12453
Leg down	2	83.33	0.50	20.00	8.78	0.11390
Leg down	3	46.67	0.70	20.00	11.13	0.08985
Leg down	4	120.00	0.10	20.00	10.38	0.09634
Duty factor	1	10.00	0.50	20.00	7.82	0.12788
Duty factor	2	10.00	0.50	20.00	6.88	0.14535
Duty factor	3	10.00	0.50	20.00	8.19	0.12210
Duty factor	4	10.00	0.50	20.00	9.12	0.10965
Leg sweep	1	10.00	0.50	20.00	9.50	0.10526
Leg sweep	2	10.00	0.50	126.67	7.72	0.12953
Leg sweep	3	10.00	0.50	73.33	11.85	0.08439
Leg sweep	4	10.00	0.50	180.00	6.93	0.14430
Iteration 3						

Initial parameter values		**Leg down**	**Duty factor**	**Leg sweep**	**Time (sec)**	**Speed (m/s)**
		10.00	0.50	180.00	6.93	0.14430
What is changed		**Leg down**	**Duty factor**	**Leg sweep**	**Time (sec)**	**Speed (m/s)**
Leg down	1	10.00	0.50	180.00	6.94	0.14409
Leg down	2	83.33	0.50	180.00	7.47	0.13387
Leg down	3	46.67	0.50	180.00	6.91	0.14472
Leg down	4	120.00	0.50	180.00	6.97	0.14347
Duty factor	1	46.67	0.30	180.00	7.59	0.13175
Duty factor	2	46.67	0.50	180.00	7.12	0.14045
Duty factor	3	46.67	0.70	180.00	7.16	0.13966
Duty factor	4	46.67	0.10	180.00	11.35	0.08811
Leg sweep	1	46.67	0.50	20.00	7.06	0.14164
Leg sweep	2	46.67	0.50	126.67	7.38	0.13550
Leg sweep	3	46.67	0.50	73.33	6.84	0.14620
Leg sweep	4	46.67	0.50	180.00	6.90	0.14493
Iteration 4						
Initial parameter values		**Leg down**	**Duty factor**	**Leg sweep**	**Time (sec)**	**Speed (m/s)**
		46.67	0.50	73.33	6.84	0.14620
What is changed		**Leg down**	**Duty factor**	**Leg sweep**	**Time (sec)**	**Speed (m/s)**
Leg down	1	10.00	0.50	73.33	12.03	0.08313
Leg down	2	83.33	0.50	73.33	7.12	0.14045
Leg down	3	46.67	0.50	73.33	6.65	0.15038
Leg down	4	120.00	0.50	73.33	7.65	0.13072
Duty factor	1	46.67	0.30	73.33	7.47	0.13387
Duty factor	2	46.67	0.50	73.33	6.66	0.15015
Duty factor	3	46.67	0.70	73.33	6.88	0.14535
Duty factor	4	46.67	0.10	73.33	9.29	0.10764
Leg sweep	1	46.67	0.50	20.00	7.93	0.12610
Leg sweep	2	46.67	0.50	126.67	7.00	0.14286
Leg sweep	3	46.67	0.50	73.33	6.62	0.15106
Leg sweep	4	46.67	0.50	180.00	6.91	0.14472
Final Results		**Leg down**	**Duty factor**	**Leg sweep**	**Time (sec)**	**Speed (m/s)**
		46.67	0.50	73.33	6.62	0.15106

Table 6: Coordinate Descent on Walking Time Results. Version 2.

3.3 Discussion

3.3.1 Limitations

The performance of the robot that is optimized in the project is the walking speed. Robot walking speed is an important factor to determine the performance of hexapods, but other parameters such as energy consumption, stability, and payload capacity are equally important. Only considering the walking speed as the single factor to determine the robot's performance is not sufficient. In fact, for a number of cases, the robot is not able to walk in a straight line or the robot base collides the ground during walking are observed.

The optimization process is experiment-based, which means that the robot needs to be set to run for every parameter change. For every single parameter, three walking data are recorded, and the walking speed is calculated based on the average value of them. In order to minimize the operation process, only 7 values are chosen for each control parameter, which may cause issues when determining the optimal value. Increasing this grid size may improve the resolution up to which the optimal value may be determined. With the current method, the optimal value is likely to appear between two numbers in the list but the exact value cannot be determined. We may also consider `grid refinement' strategies, using a coarse grid initially and then a fine grid later on.

In the experiment, a modified coordinate descent optimization is conducted, which is a simplified version of coordinate descent method. The optimal value is determined from the list of 7 or 8 values for each parameter based on the robot walking speed. The more accurate way is to fit the best fit curve to the speed data over parameter values and then determining the local maximum of that best-fit curve and repeat this in every direction. The optimal parameter value can be achieved from the peak point, as well as the maximum walking speed.

Walking distance for both parameter sweeps and coordinate descent is set to be 1 meter. During the experiment, the motors that actuate the legs do not work consistently. Multiple times of pause and breaks are observed during the operation, especially under extreme parameter values. The inconsistency will affect the actual performance of the robot significantly in a short distance. The deviation for three runs in the trial as well as the trial to trial consistency will be influenced.

Note that the classical coordinate descent algorithm need not produce a global optimum, so the solutions we obtained need to be considered to be likely local optima. One way to test (but not prove) global optimality is to start the optimization from many initial seeds and see if they all roughly converge to the same optimum.

3.3.2 Possible source of error

The performance data for parameter sweeps are measured with video analysis. The video of the robot operating under various parameters is analyzed frame by frame to calculate the total run time. The video has an FPS of 30 (30 frames per second) and sometimes may not be enough. The robot may reach the end line between the frames and potential human error may affect the data collection. Similar problems are also the cause of potential error during coordinate descent data collection. Due to the limited access to motion capture instruments in the research lab, a stopwatch is used to measure the walking time during coordinate descent. Human error may be involved in the process and this random error can be minimized by collecting multiple trials of data. For such hand-timed trials, systematic error may occur based on the human reaction time and may potentially affect the results. It may be possible to estimate the random and systematic error in the human stop-watch-based timing by comparing the human timing with video-based analysis, treating the latter as much more accurate.

Hardware defects of the robot itself may affect the performance during operation, which also causes the error. The center of gravity should be in the middle of the rectangle base of the robot to ensure the balance during walking. The actual center of gravity is located slightly towards the back of the base. The deviation of the center of gravity has little impact on the performance when the robot is operating under parameters that close to default settings. However, the robot is observed to lean to front and back under some values of the leg down angle. For instance, for some parameter values, the robot body touches the ground, and this results in inconsistent walking time data. The inconsistency in leg surface material and friction is another source of error. The robot legs are made from 3D printing and the material is ABS plastic, which has low friction. In order to increase the friction, a plastic spray is applied to each leg, but the plastic is not evenly distributed on the surface of curved legs. The inconsistency of leg surfaces will stop the robot moving in a straight line, which causes errors in data collection. Finally, another issue to contend with during such optimization is the robot hardware properties slowly changing with time: for instance, wear of the leg surfaces (which we do not believe is an issue here) and battery discharging over time. We did not explicitly account for such slow changes in this work, although the battery was kept well-charged during the trials.

Chapter 4: Conclusion and Future Work

The project consists of two parts: the assembly and fabrication of MiniRHex hexapods and the robot walking speed optimization. The main body components of the robot including motor sleeves, motor shafts, legs, and battery holds are 3D printed with ABS plastic. The base of the robot is made from the acrylic board with lacer cutting. The optimization of walking speed is based on parameter sweep and coordinate descent methods. The parameter sweeps are performed on duty factor, leg down angle, and leg sweep width angle. Each parameter sweep gives a local maximum walking speed and a local optimal parameter value, with fixed values of the other parameters. Coordinate descent is the co-optimization of the three control parameters. In order to improve the efficiency of the data collection process, a modified coordinate descent method is used in the experiment. The results of the optimization are three optimal values of three control parameters chosen from a list of 7 values for each parameter. The maximum walking speed is achieved under the optimal parameter values.

The coordinate descent optimization can be made more efficient by automating the process as we had originally planned and partially implemented. The motion capture, remote control treadmill, and wireless code update are the key technologies to fully automate the optimization process. The automation of the optimization process allows a much higher resolution of parameter lists. The coordinate descent can be conducted for numbers of iterations until the results converge. More control parameters can be optimized at the same time. Other optimization methods can be applied to improve performance such as gradient descent. More control parameters may also be considered in the optimization process such as phase coherence. The performance of the robot can be measured in other ways. The energy consumption, robot walking stability, as well as the payload capacity.

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